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Long-term changes in precipitation phase in Europe in cold half year

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ABSTRACT

The change in precipitation phase is an important manifestation of climate change, especially in the moderate climate zone and mountain regions. We analyse changes in precipitation at 107 European stations in cold months (November–April). Stations in Czechia where both surface synoptic observations (SYNOP) reporting the precipitation phase, and temperature and precipitation data are available in sufficient quality, are used to determine the regional threshold temperature. The threshold temperature is then applied to separate solid and liquid precipitation phase in cold months at European stations in 1961–2010. If daily mean temperature is higher than the regional threshold temperature, daily precipitation amount is considered to be liquid and vice versa. The value of the regional threshold temperature is 1.1 °C. The ratio of solid to total precipitation (S/P) significantly declines over large parts of Europe. The strongest negative trend is detected in the belt stretching from the coast of northern Scandinavia through central and eastern Europe towards southern and southeastern Europe. The trend of S/P ranges from −0.2 to −0.9%·year^{-1} there. The average annual trend of the ratio of solid precipitation for all Europe is −0.12%·year^{-1}. The magnitude of the trend of the ratio of solid precipitation exhibits only a minor sensitivity to the choice of the threshold temperature. A comparison with real trends, calculated for stations in Czechia, indicates that trends determined from the threshold temperature tend to be overestimated, that is, the decline of solid precipitation in Europe is even faster that what results of this study indicate.

1. Introduction

Various characteristics of precipitation have been studied in relation to ongoing climate change, such as precipitation amounts (e.g., Becker et al., 2013; Dai et al., 1997; New et al., 2001; Smith et al., 2012), extremes (e.g., Allan and Soden, 2008; Frich et al., 2002; O'Gorman O'Gorman, 2015; van den Besselaar et al., 2013; Villarini et al., 2013), and intensity (e.g., Berg et al., 2013; Brunetti et al., 2000; Cioffi et al., 2015; Maraun et al., 2008; Osborn et al., 2000; Ye et al., 2016). However, less attention has been paid to the change in precipitation phase, although it may be used as a suitable indicator of changing climate, especially where winter temperatures typically occur in the vicinity of zero. Particularly striking is the lack of studies on the long-term change of precipitation phases in Europe. We are aware of only four such studies, all of them being local or regional in their scope. Twardosz et al. (2012) analyse a single station (Krakow) in Poland, while Irannezhad et al. (2017) investigate three stations in Finland. Marty and Meister (2012) and Schöner et al. (2009) focus on precipitation phase changes in high mountain environment in the Alps. This study, therefore, attempts to fill the gap in our knowledge by analysing changes in the precipitation phase in Europe as a whole.

Long-term changes in precipitation phase are usually expressed as trends in the ratio of solid to total precipitation (S/P) amount. However, some issues are connected with S/P. Huntington et al. (2004) explain its major disadvantage: a change in S/P carries no information on how solid or liquid precipitation amounts change; that is, even if a change of S/P is detected, no change of solid precipitation may in fact be present because of a trend in total precipitation. This effect is particularly important when the change of S/P is calculated for the whole year: if, for example, the amount of solid precipitation does not change and total precipitation amount increases due to an increase in summer precipitation (which is liquid), S/P declines although solid precipitation remains constant. Because of that, it is relevant to also study changes in the occurrence of the individual precipitation phase and precipitation totals, not only in S/P.

The negative trend in S/P prevails in most studies. Marty and Meister (2012) found a significant decrease of S/P of −0.125%·year^{-1} at Sonnblick (3105 m a.s.l.) and Weissfluhjoch (2690 m a.s.l.) stations, although Schöner et al. (2009) revealed no significant changes in S/P at high elevations. A significant increase in total precipitation but almost

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no change in solid precipitation were detected in Krakow since 1863 (Twardosz et al., 2012). Irannezhad et al. (2017) assigned precipitation phase by snowmelt model and found statistical significant decrease in S/P at all three stations in Finland between 1909 and 2008. In China, both Gillies et al. (2012) and Guo and Li (2015) found decrease in S/P. Gillies et al. (2012) detected a rapid decline of S/P in ERA-40 reanalysis in central and eastern China where the average reduction of S/P was 8.5% per decade after 1970. The authors explained such a rapid decrease by a warming of lower troposphere, which is accompanied by increased moisture and decreased evapotranspiration. They pointed out to the influence of the weakening Siberian high (Panagiotopoulos et al., 2005), which causes a weaker advection of cold air to China. Guo and Li (2015) found a negative trend of S/P (−0.6% per decade) in the Tian Shan Mountains, but only after the early 1980s. According to Feng and Hu (2007), the largest decrease of S/P occurred in the central USA and in the Pacific Northwest, the average reduction over all stations being −2.7% and −1.5% per decade, respectively. This is in agreement with Knowles et al. (2006) who found a decline in S/P at 74% of stations in the Northwest USA. However, the decrease in S/P is not spatially uniform: some regions, such as eastern USA (Feng and Hu, 2007), do not exhibit clear trends in S/P. Furthermore, increase in S/P has been observed particularly in cold areas, such as in northern Canada (Vincent et al., 2015) and perhaps over vast areas in Eurasia during 1998–2012 where Li et al. (2015) confirmed winter cooling, which might have led to increase in S/P there. At a local scale, increasing wintertime snowfall was also observed in the Lake Michigan region (Clark et al., 2016).

The climatological observations are made in a daily step, that is, are recorded once in 24 h. As a result, one value of daily precipitation amount may correspond to different precipitation phases when both rain and snow fall during a single day. This constitutes a substantial difficulty when one attempts to attribute precipitation amounts to an individual precipitation phase and requires simplifications in such an attribution unless the amounts are recorded separately for each precipitation phase, which is rarely the case. Generally, there are five basic approaches to the determination of precipitation phase and its attribution to daily precipitation amounts: (1) If snowfall is recorded, all daily precipitation is considered as snow (Feng and Hu, 2007; Guo and Li, 2015; Huntington et al., 2004; Knowles et al., 2006; Serquet et al., 2011). (2) Precipitation phase is determined from the SYNOP (surface synoptic observations) reports; (sub)daily precipitation amount may be regarded as solid, mixed, or liquid then (Dai, 2008; Jennings et al., 2018; Ye et al., 2013). (3) The proportion of solid to total precipitation is estimated by function. Parametric function is fitted to the dependence of the probability of solid precipitation on temperature. For example, Schöner and Böhm (2007) and Jennings et al. (2018) use tangent function for this purpose. (4) Precipitation phase is estimated by hydrological or snowpack models (Froidurot et al., 2014; Harder and Pomeroy, 2014; Irannezhad et al., 2017; Zanotti et al., 2004), which is further used for various hydrological applications. (5) Threshold temperature is used to determine the precipitation phase (e. g. Auer, 1974; Feiccabrino and Lundberg, 2008; L'hôte et al., 2005; Ye et al., 2013, Zhong et al., 2018). Threshold temperature (T_t) is temperature for which the probability of solid and liquid precipitation phase is the same (50%). If temperature is higher than T_t, daily precipitation is considered liquid and vice versa.

The selection of the suitable method for assignment of precipitation phase to precipitation amount is affected by the availability of data. The most accurate method is the determination of precipitation phase by SYNOP reports because SYNOP reports contain real observed information about precipitation phase. However, there are several issues with SYNOP reports such as a varied quality and insufficient length of time series. Furthermore, SYNOP reports are not available at every station with climatic data in sufficient quality and in sufficient length. Fortunately, stations in Czechia provide temperature data and SYNOP reports in good quality. Thus, we use data at Czech stations for the estimation of threshold temperature, which is further used at European stations to determine the precipitation phase only from temperature and precipitation data.

Maximum, minimum, daily mean temperature (Fuchs et al., 2000; L'hôte et al., 2005; Zanotti et al., 2004), dew point temperature (Ye et al., 2013), and wet-bulb temperature (Ding et al., 2014; Marks et al., 2013; Sims and Liu, 2015) have been used as T_t in various studies. Ye et al. (2013) prefer dew point temperature to daily mean temperature because the former is less sensitive to relative humidity and elevation, while on the other hand, Sims and Liu (2015) favour wet-bulb temperature. However, daily mean temperature predominates in most studies. The mixed precipitation category cannot be defined by a single T_t; two threshold temperatures are needed to delineate it (Dai, 2008; Fuchs et al., 2000; Zanotti et al., 2004), lower T_t discriminating solid from mixed precipitation then, while higher T_t distinguishing mixed and liquid precipitation. The mixed precipitation amount can be analyzed as a separate category or alternatively, it can be divided to contribute into solid and liquid precipitation.

Threshold daily mean temperature that separates solid from liquid precipitation ranges roughly from −1.0 °C to +4.0 °C in literature. Such a large spread is caused by many factors, such as altitude, air pressure, density of air mass, speed of falling snow particles, topography, local winds, and urban heat island (Dai, 2008; Ding et al., 2014; Kienzle, 2008; Liu and Chen, 2016; Rajagopal and Harpold, 2016; Ye et al., 2013; Zhong et al., 2018), but relative humidity appears to be the most important factor that modifies the value of T_t at large spatial scales.

Ye et al. (2013) studied the effect of relative humidity on T_t across Eurasia. The decrease of relative humidity towards central Eurasia closely corresponds to the distinct growth of T_t. Jennings et al. (2018) also reported high T_t in central Asia, where the highest values approaching +4.5 °C occur in the vicinity of Tibetan Plateau. Generally, the lower relative humidity, the higher T_t (Ding et al., 2014). The reason for this is that relative humidity affects the melting of solid particles: if the air mass at surface is saturated, water vapour condensates on solid particles more easily, which leads to a release of latent heat and faster melting of them (Ding et al., 2014; Matsuo and Sasyo, 1981). If relative humidity is low, the melting of solid precipitation particles is suppressed due to a smaller release of latent heat, which causes solid precipitation falling at higher temperatures. This process leads to higher values of T_t.

2. Data and methods

All the analyses in this paper cover cold half year, that is, months November to April, unless otherwise stated. Ten stations in Czechia and 107 stations in Europe are used in this study. The data from Czech stations (see Fig. 1 and Table 1) are used to determine threshold temperature separating the solid from liquid precipitation phase. They consist of SYNOP reports where precipitation types are specified and climatological data, such as daily mean, maximum, and minimum temperature, and daily precipitation amount are included. These data are available for every day from November to April in period 1982–2006 (with the exception of Kuchařovice, which ends in 1997). Term 'precipitation type' refers to a given form of precipitation (e. g. snow, ice pellets, drizzle), while term 'precipitation phase' (solid, liquid, mixed) is more general and includes various precipitation types.

The European station data (Fig. 1) are obtained from the European Climate Assessment & Dataset (Klein Tank et al., 2002). Regions with low proportion of solid precipitation are not considered in this study (e.g. southern and southwestern Europe). We use daily mean temperature and daily precipitation data between 1961 and 2010 from November to April. The choice of the cold half year reflects the fact that in the vast majority of the analyzed region, solid precipitation (with the exception of hail) is not observed at all or is only marginal in the warm half year, the inclusion of which would only dilute the signal that we seek for. Additionally, most of the papers on the S/P trends referenced

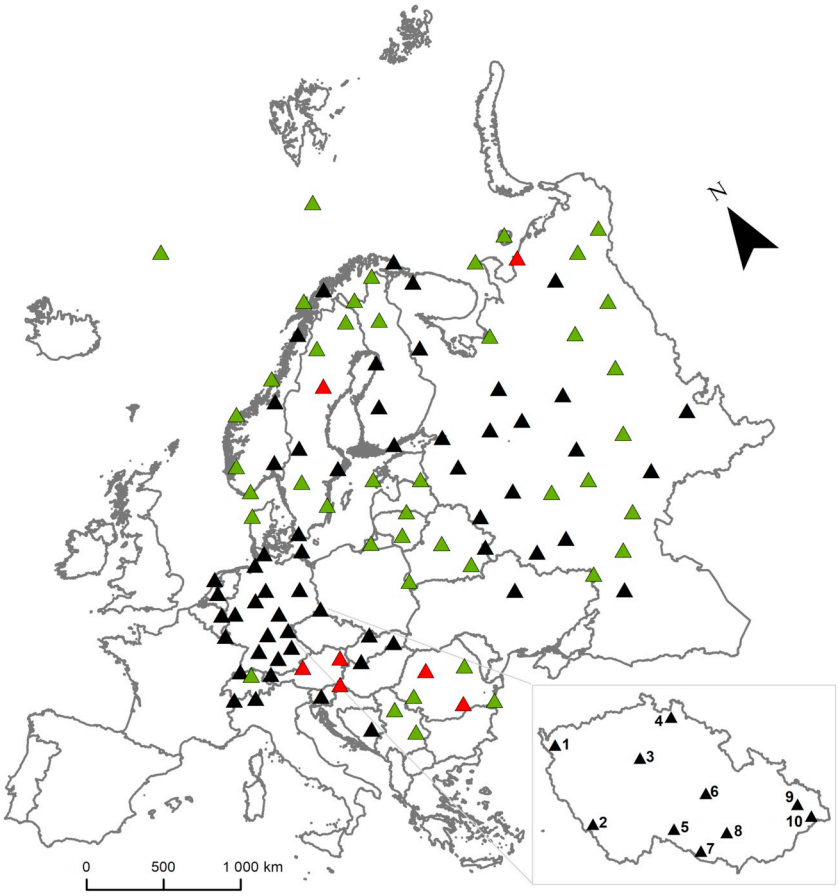

Fig. 1. Locations of European stations. Colours represent number of missing years at station: black (0); green (1–3) and red (4–5). Locations of Czech stations together with identifying number are displayed in right bottom corner. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

above (i.e. Knowles et al., 2006; Feng and Hu, 2007; Serquet et al., 2011; Gillies et al., 2012; Twardosz et al., 2012; Guo and Li, 2015; Clark et al., 2016) analyse precipitation phase and its long-term changes in the cold period of year only. We choose stations with a maximum of five missing years; the missing year is defined here as a year with 15 or more days in which temperature or precipitation data are not recorded. The total number of missing years over all stations is 114; they are omitted from further analyses, making 50 (47% of European stations) station series incomplete (Fig. 1).

A simple linear regression is used to determine the long-term trends in the cold months (November–April) of S/P (%·year^{-1}) and of total, solid, mixed, and liquid precipitation amounts (all in mm·year^{-1}) at the Czech and European stations. Statistical significance is tested by Student's *t*-test at the 5% and 10% levels.

2.1. Estimation of threshold temperature

Threshold temperature may be estimated only from stations where both SYNOP reports and daily temperature and precipitation records are available. SYNOP reports in sufficient quality are available to us at the Czech stations; that is why they form a basis for the estimation of threshold temperature. The SYNOP reports are compiled every hour, that is, 24 SYNOP reports are available during a day; however, at several stations, the time interval was extended to 3 h in the 1980's (i.e., eight SYNOP reports a day are available). SYNOP reports contain information on 'weather conditions,' several codes of which describe precipitation type at the time of observation or during the last observation period (1 or 3 h).

The occurrence of precipitation types during a specific day determines whether daily precipitation amount is considered as solid or liquid precipitation (if only solid or liquid precipitation types are recorded, respectively) or mixed precipitation (if either both solid and liquid precipitation types are recorded or a mixed precipitation type is recorded). The time series of the ratio of solid to total precipitation (S/P) for precipitation phases defined in this way (i.e., containing solid, mixed, and liquid precipitation as separate phases) is referred to as 'exact S/P,' because it is directly based on measured data and should be most accurate, therefore.

Nevertheless, single T_t must be estimated from data that only contain solid and liquid precipitation. This means that mixed precipitation amounts should be divided into solid and liquid precipitation. The division is performed with the use of SYNOP reports: the total precipitation amount on days with mixed precipitation is first divided into the liquid, mixed, and solid parts proportionally to the number of hourly (or three-hourly) observations when the particular precipitation phase occurred. That is, we assume that the precipitation intensity is the same in all periods (hours or 3 h) when precipitation is recorded, regardless of the precipitation phase and type. Finally, the amount of mixed precipitation is split equally into the liquid and solid precipitation: a half of the amount in every hour (or 3 h) period with mixed precipitation is assigned to liquid precipitation and a half to solid precipitation. As a result, solid precipitation for the purpose of estimating the threshold temperature is the sum of (i) precipitation totals on days with solid precipitation, (ii) solid precipitation on days with mixed precipitation, and (iii) half of mixed precipitation; and analogously for liquid precipitation.

The proportion (probability) of solid and liquid precipitation is calculated for every tenth of °C at all Czech stations together between November and April. We calculate this for maximum, minimum, and daily mean temperature to determine which temperature indicator is most appropriate to discriminate between solid and liquid precipitation. Since the dependence of the probability of precipitation phases is less smooth for maximum and minimum daily temperature than for daily mean temperature, the latter is preferred for the determination of

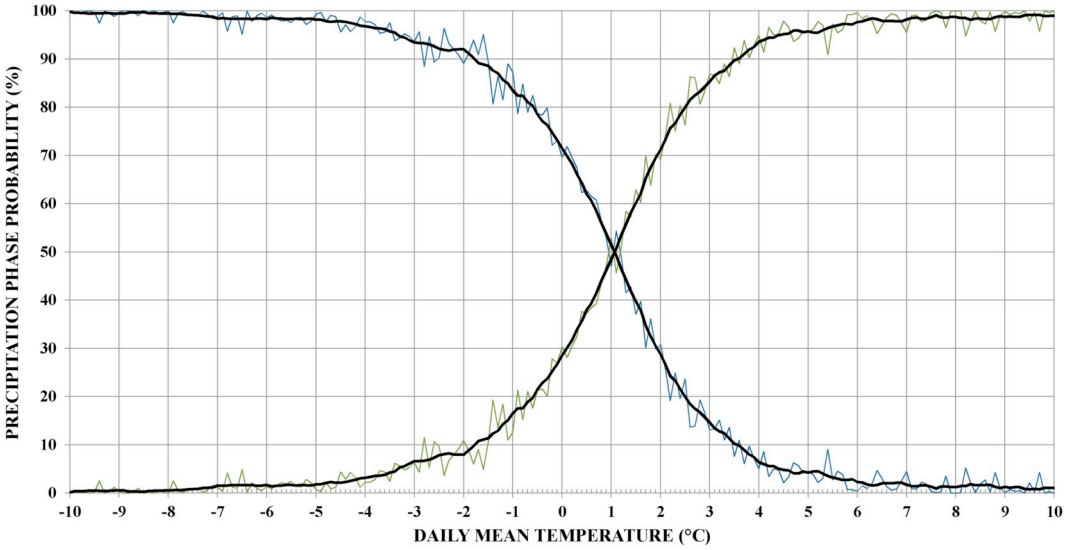

Fig. 2. Dependence of probability of solid (blue line) and liquid (green line) precipitation on daily mean temperature at all Czech stations together (1982–2006, November–April). Black lines represent moving average for 1.1 °C interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

threshold temperature. The dependence of probability of solid and liquid precipitation on mean temperature is shown in Fig. 2. The probability of solid precipitation declines with rising temperature, while the dependence is opposite for liquid precipitation, as expected. T_t is temperature at the crossing point where the probability of both precipitation phases is equal. Fig. 2 suggests that the threshold mean temperature is +1.1 °C. This value is further called regional threshold temperature (regional T_t) and the S/P time series determined by this threshold temperature by assigning liquid phase to precipitation falling at temperatures equal to and above T_t and solid phase to precipitation falling at temperatures below T_t is called regional temperature-based S/P.

T_t was also calculated at individual Czech stations separately (local T_t). Local T_t ranges from 0.2 °C to 1.8 °C (see Table 1), which points to a considerable influence of station microclimate on local T_t, as mentioned in Section 1. We prefer to use regional T_t in further analysis because the dependence of the probability of precipitation phase on temperature is much smoother for data pooled over stations than for individual stations and the regional threshold temperature can be determined with less uncertainty, therefore.

Fig. 2 also demonstrates quite a high probability of solid precipitation at temperatures above regional T_t, and of liquid precipitation at temperatures below it. This fact has at least four different explanations. The first reason is the absence of the mixed precipitation category, whose occurrence is most probable at temperatures near T_t. A substantial part of the uncertainty in the precipitation assignment to the solid and liquid precipitation near T_t is a consequence of the separation of mixed precipitation. The second explanation is related to atmospheric fronts, which are typically accompanied by a rapid temperature change, which may not be captured in daily mean temperature well or at all if a front passes early or late in a day. For example, if a cold front accompanied with snow passes in the evening, solid precipitation occurs even if daily mean temperature is considerably higher than T_t. The third explanation is the occurrence of freezing rain and freezing drizzle. These precipitation types are categorised as liquid precipitation, although their occurrence is mostly tied to surface temperatures below 0 °C. In warmer air aloft with temperature above 0 °C, these precipitation types fall as rain until they reach cold ground where rain and drizzle become frozen. The last explanation points to specific meteorological conditions (e.g., relative humidity), which can cause solid (liquid) precipitation to occur at temperatures above (below) T_t.

We are aware of the fact that the length of time series at Czech stations (1982–2006), which are used for determination of regional T_t, is shorter than European data, to which it is applied (1961–2010). Nevertheless, a different length of time series is unlikely to have a considerable influence on the value of regional T_t, which is further proven by a close correspondence of regional T_t determined at Czech stations with values in other studies, e. g. +1.2 °C (over land globally) in Dai (2008), +1.0 °C (over land in the Northern Hemisphere) in Jennings et al. (2018) and equally +1.0 °C (for Sweden) in Feiccabrino and Lundberg (2008). Moreover, Jennings et al. (2018) found that T_t is generally in the vicinity of +1.0 over Europe with the highest values observed in the mountains (Pyrenees, Alps, and Scandinavian Mountains).

We also calculated T_t in cold months at seven stations in northern Europe (Norway, Finland, Russia, see Table 2) where SYNOP reports are accessible from the Ogimet database (https://www.ogimet.com/getsynop_help.phtml) between 2000 and 2018. However, the database is not sufficiently complete: some reports do not contain information on precipitation type and some of them are entirely missing, making the determination of T_t less reliable. The range of T_t at these stations (Table 2) is between 0.7 °C (Ähtäri) and 2.2 °C (Murmansk), being rather similar to local T_t determined at the Czech stations (0.2–1.8 °C). Station T_t varies considerably not only over northern Europe but even over a small area such as the Czech Republic.

One may argue that regional T_t based on observations from central Europe should not be used as an indicator of precipitation phase in distant European areas because its value may be different there. To investigate this, we compare the exact time series of S/P (in which mixed precipitation is separated into solid and liquid forms; see above) at the Czech stations with local temperature-based S/P (that is, local T_t is calculated at each station separately), regional temperature-based S/P (T_t = 1.1 °C), and with S/P determined from a range of other threshold temperatures (from −1.0 °C to +2.0 °C). The series are compared by mean absolute difference (MAD) in Table 1. The exact S/P time series represents reality since it is calculated from real observations, whereas temperature-based S/P series are based upon derived values. The match with exact S/P is closest for local T_t at most stations. Besides local T_t, the lowest MADs are found for threshold temperatures of 0.5 °C (four stations), 1.1 °C (three stations), 1.5 °C (two stations) and 0.0 °C (one station). Since values of MADs between regional and local temperature-based S/P are fairly close to each other (Table 1), and

because the value of MAD for regional T_t is within the three lowest MADs at all stations except Lysá hora (which has the lowest local T_t of all stations), we conclude that regional T_t may also be used as a precipitation phase indicator at all European stations. In any case, it is the only way that we can proceed given the availability of data.

In the next step, we compare trends of the regional temperature-based S/P with the exact S/P series at the Czech stations. Fig. 3 shows that trends of regional temperature-based S/P (blue columns) tend to be less negative (i.e., S/P declines slower) than trends of exact S/P (red columns) at most stations. A possible explanation is that this may be a result of missing mixed precipitation in the former. To investigate this, trends of exact S/P and exact S/P with mixed precipitation completely omitted (S/P without mixed precipitation) are compared at stations. Fig. 3 illustrates that differences between the exact S/P series with and without mixed precipitation are quite large at some stations (Kostelní Myslová, Svratouch, Churáňov), indicating that whether mixed precipitation is considered as discarded has mostly negative impact on trend of S/P. However, the omission of the mixed category does not considerably influence trends of S/P at most stations because the differences in trends of exact S/P with and without mixed precipitation are quite small (the difference is only 0.03%·year^{-1} for all Czech stations). In conclusion, differences between the exact S/P series (based on SYNOP; with mixed precipitation) and regional temperature-based series (based on regional T_t; without mixed precipitation) do not seem to be caused by the absence of mixed precipitation at most stations. The most important implication is that the use of regional T_t as the precipitation phase indicator is accompanied by a tendency towards a positive bias of the S/P trend.

2.2. Changes in precipitation phase in Europe

Regional T_t, which was determined at Czech stations, is used to determine precipitation phase in cold months at European stations where SYNOP reports are not available at all stations to us. Daily precipitation is considered as solid (liquid) if daily mean temperature is lower (higher) than regional T_t. As is expected, the S/P ratio increases with declining temperature towards eastern and northern Europe (Fig. 4). As is evident from Fig. 4, warm Gulf Stream affects the western coast of the Scandinavian Peninsula where S/P is much lower than in the interior of Scandinavia.

Fig. 5a shows that S/P declines at most stations, which means an increasing proportion of liquid precipitation and a decreasing proportion of solid precipitation. There are only four stations in Russia with a positive, but insignificant, trend of S/P. The southwest–northeast gradient is evident as the trend of S/P becomes less negative towards the northeast. Simultaneously, the number of stations with significant negative trends also tends to decrease towards northeast, although significant negative trends occur on the Barents Sea coast. The area of strong S/P decrease begins on the north Scandinavian coast and continues through central Europe to southern (Serbia, Romania) and southeastern Europe (Belarus, Ukraine and southern Russia). The negative trend of S/P is statistically significant (at the 5% level) at most stations in this belt. At almost all stations there, a decrease in solid precipitation is observed (Fig. 5b). On the other hand, the trend in liquid precipitation is generally positive at the majority of stations, most notably in Scandinavia where the rise of liquid precipitation is particularly strong, although some slight negative trends are present in southern and central Europe (Fig. 5c). This illustrates the fact that regardless of a general negative trend of S/P, trends in liquid and solid precipitation may vary. For example, both precipitation phases and total precipitation amount increase in northern Scandinavia; yet the trend of S/P is negative due to a slower increase of solid then liquid precipitation. On the other hand, negative trend in both precipitation phases and total precipitation amount is recorded at some stations in southern Germany. Because of a stronger decrease of solid than liquid precipitation, the trend of S/P is negative there as well. Nevertheless, in general, the negative trend of S/P is mostly related to a decrease of solid and/or increase of liquid precipitation, whereas the change of total precipitation amount is of varied sign and insignificant at most stations, except Scandinavia where significant increases in total precipitation are observed (Fig. 5d).

The trend of S/P is mostly negative also in northern and interior parts of Norway, Sweden, and Finland. S/P exceeds 80% at almost all stations in this region, and both precipitation phases generally increase there with a stronger increase in liquid precipitation. Stations with significant negative S/P trends are located on a coast, which may be explained by Scandinavian Mountains since it represents a natural barrier separating the Scandinavian interior from the Atlantic Ocean.

In Russia (except its southern part) and the Baltic states, all stations show a positive trend in liquid precipitation, while varied trends are observed in solid precipitation. The trend in S/P is mostly negative, but statistically insignificant at most stations with the exception of the Barents Sea coast.

Although time series of S/P strongly depend on the location of

Table 2
Threshold temperatures (T_t) at selected European stations (November–April 2000–2018) based on Ogimet database.

Station	State	T_t
Ähtäri	Finland	0.7 °C
Bodø	Norway	1.7 °C
Murmansk	Russia	2.2 °C
St. Petersburg	Russia	1.5 °C
Sodankylä	Finland	1.9 °C
Tromsø	Norway	0.9 °C
Værnes	Norway	1.5 °C

Table 1
Local threshold temperature (°C) and the mean absolute annual difference (MAD; in %) between exact S/P and: local temperature-based S/P (based on local T_t), and selected T_t based S/P, where T_t = 1.1 °C represents regional temperature-based S/P. Czech stations between 1982 and 2006 (November–April) with number in first column referring to station location in Fig. 1 are showed.

No	Station	Local T_t	MAD: exact vs. local S/P	MAD: exact vs. selected T_t S/P						
				−1.0	−0.5	0.0	0.5	1.1	1.5	2.0
1	Cheb	1.6	4.9	19.5	17.4	14.4	10.4	5.8	4.4	6.5
2	Churáňov	1.0	4.5	16.8	13.4	9.3	5.3	4.5	6.1	10.8
3	Praha, Ruzyně	1.8	6.8	16.0	12.9	9.5	7.0	4.7	5.2	8.2
4	Liberec	1.2	4.9	20.9	17.7	13.1	8.0	4.9	5.7	9.5
5	Kostelní Myslová	1.0	6.3	17.7	13.6	9.5	6.1	6.3	8.9	13.2
6	Svratouch	0.9	3.4	18.9	13.6	8.8	3.8	4.0	6.6	10.6
7	Kuchařovice	0.7	7.4	12.9	11.8	8.0	7.3	7.7	10.0	13.2
8	Brno, Tuřany	0.5	3.8	13.1	10.0	6.8	3.8	5.3	9.1	12.9
9	Ostrava, Mošnov	1.5	3.8	20.9	17.5	13.2	9.0	5.0	3.8	5.1
10	Lysá hora	0.2	3.0	6.2	3.9	3.1	3.5	4.9	7.4	10.0

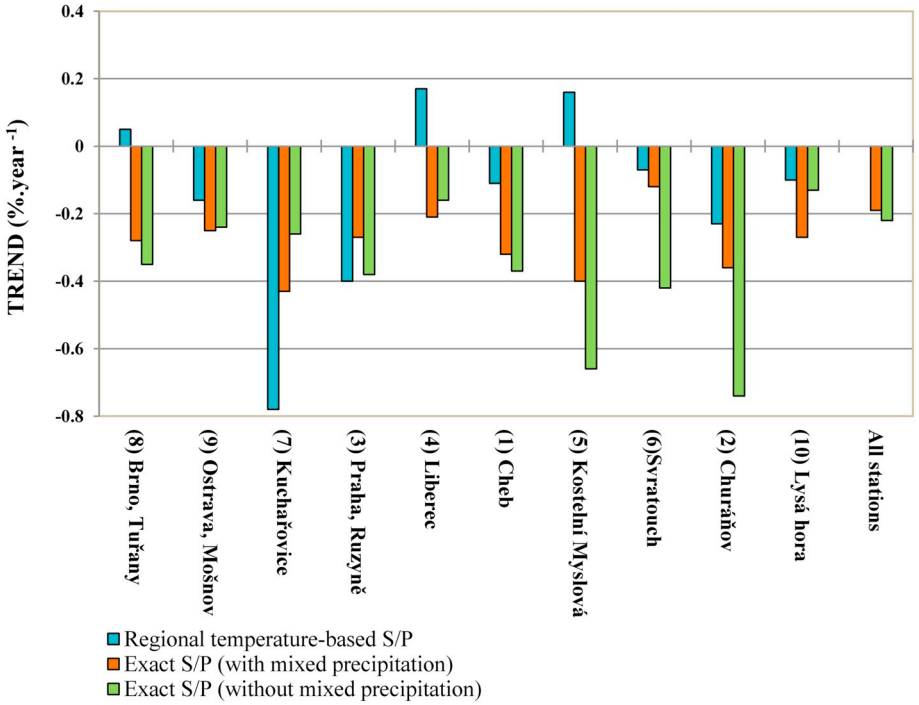

Fig. 3. Trends of regional temperature-based S/P series (blue), exact S/P series (red) and exact S/P series without mixed precipitation (green) at the Czech stations and at all Czech stations together in cold months (November–April) between 1982 and 2006. Stations are ordered by their altitude and number in bracket refers to their location in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

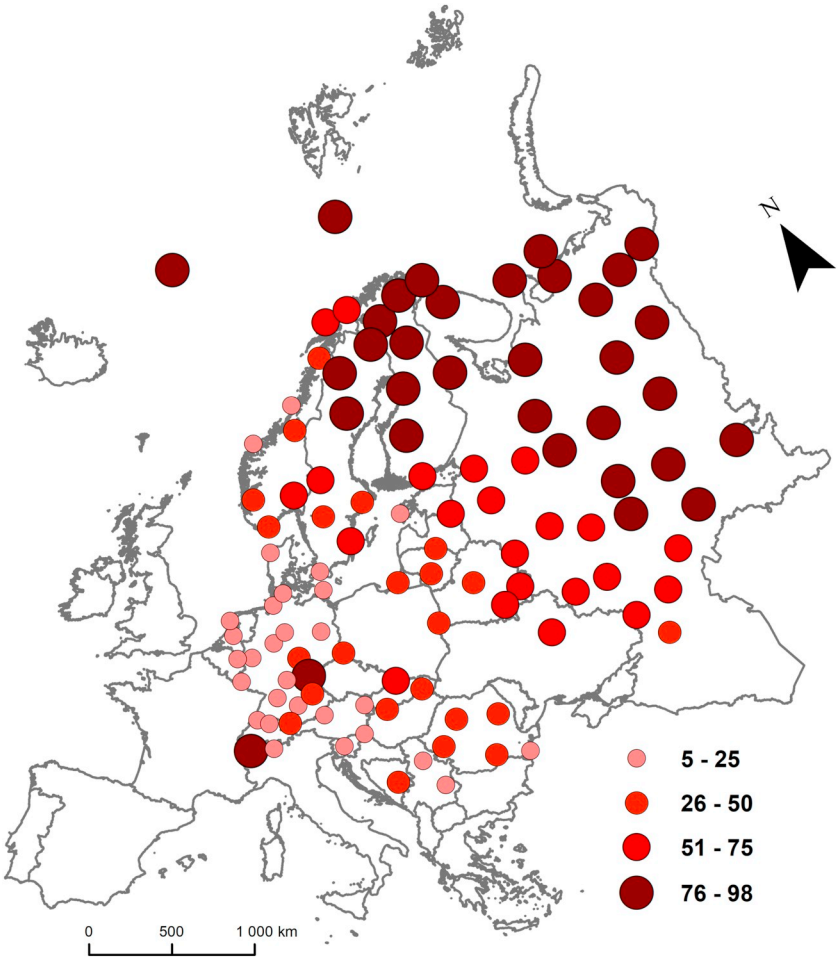

Fig. 4. Average S/P (1961–2010; in %) between November and April at European stations.

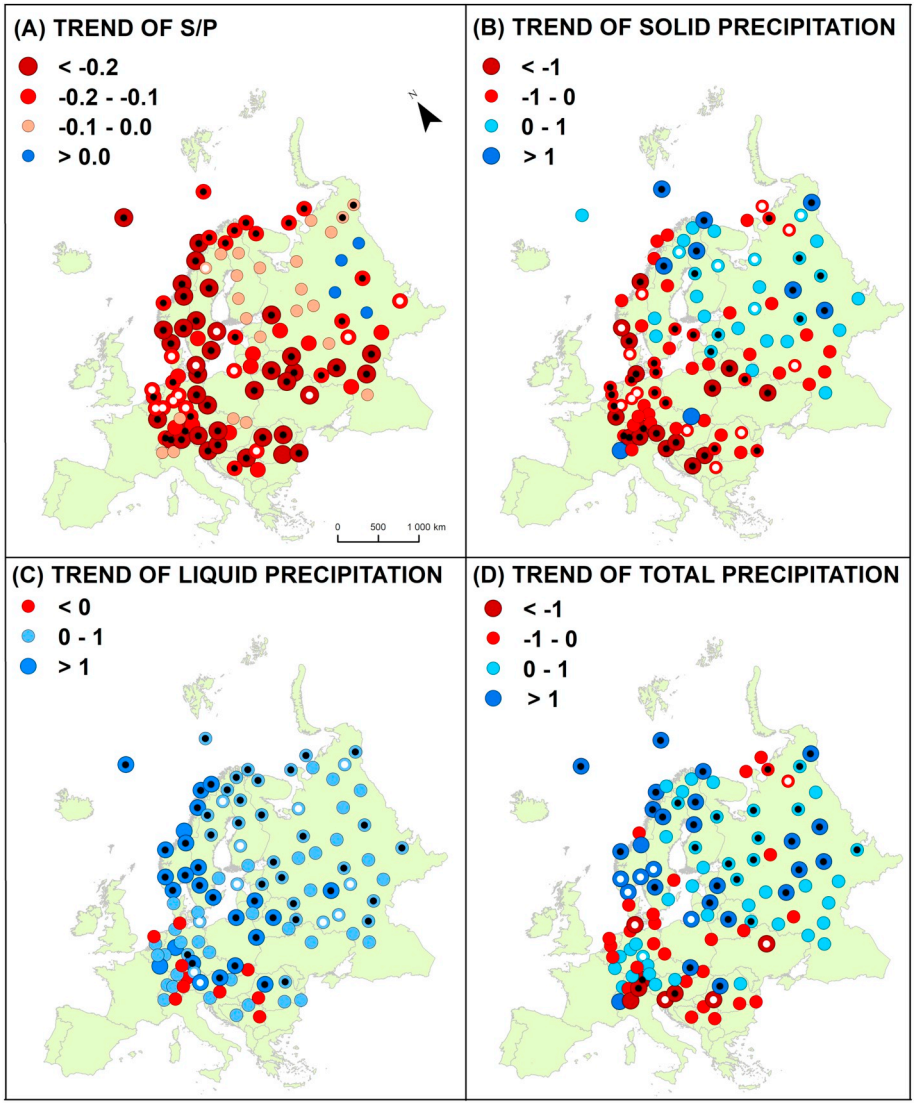

Fig. 5. Trends at European stations in cold months (November–April), 1961–2010: (a) S/P (%·year^{-1}); (b) solid precipitation (mm·year^{-1}); (c) liquid precipitation (mm·year^{-1}) and (d) total precipitation (mm·year^{-1}). Trends statistically significant at the 5% (10%) level are denoted by black (white) dots.

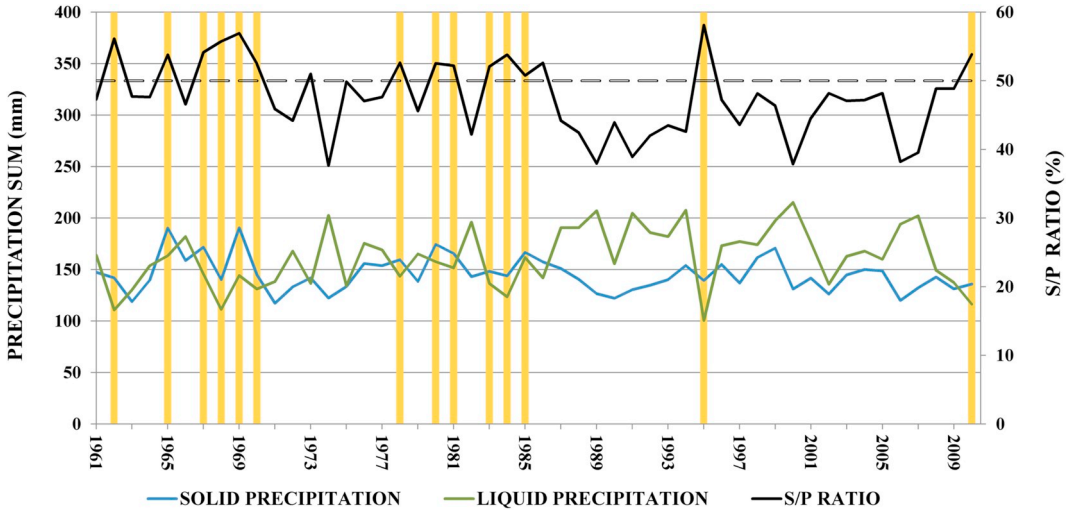

Fig. 6. Time series of mean cold months (November–April) S/P (black line, right axis) and solid (blue) and liquid (green) precipitation (left axis) for all European stations together between 1961 and 2010. Yellow strips highlight the years with a higher proportion of solid than liquid precipitation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Trends of S/P (%·year^{-1}; November–April 1961–2010) for different threshold temperatures T_t and for two threshold temperatures at selected European stations. Statistically significant values at the 5% (10%) level are denoted by two (one) asterisks. The tendency of trends to grow or decline with growing T_t is specified.

Station	Threshold temperature (°C)							Tendency of trends	Two threshold temperatures
	−1.0	−0.5	0.1	0.6	1.1	1.6	2.1		
Brest	−0.52**	−0.54**	−0.61**	−0.71**	−0.77**	−0.82**	−0.87**	Positive	−0.73**
Cuxhaven	−0.07*	−0.10**	−0.10*	−0.10*	−0.14**	−0.15*	−0.18*	Positive	−0.13*
Ljubljana	−0.12	−0.06	−0.07	−0.14*	−0.24**	−0.29**	−0.33**	Positive	−0.21**
Lund	−0.07	−0.08	−0.11	−0.16	−0.24*	−0.23*	−0.29**	Positive	−0.20*
Regensburg	−0.01	−0.04	−0.04	−0.07	−0.14	−0.23**	−0.25**	Positive	−0.12
Sauda	−0.18**	−0.17**	−0.21**	−0.29**	−0.32**	−0.40**	−0.42**	Positive	−0.31**
Kanin Nos	−0.13*	−0.15**	−0.14**	−0.15**	−0.11**	−0.08*	−0.07**	Negative	−0.09**
St. Petersburg	−0.38**	−0.35**	−0.26**	−0.24**	−0.23**	−0.19**	−0.19**	Negative	−0.22**
Sodankylä	−0.22**	−0.16**	−0.09	−0.07	−0.07	−0.02	−0.04	Negative	−0.06
Tromsø	−0.35**	−0.31**	−0.23**	−0.20**	−0.19**	−0.15**	−0.16**	Negative	−0.19**
Vardø	−0.35**	−0.29**	−0.25**	−0.20**	−0.16**	−0.14**	−0.08**	Negative	−0.18**
Ähtäri	−0.14	−0.09	−0.08	−0.09	−0.09	−0.09	−0.06	Various	−0.09
Bacău	−0.26**	−0.29**	−0.33**	−0.41**	−0.37**	−0.35**	−0.34**	Various	−0.34**
Kursk	−0.21**	−0.21**	−0.26**	−0.21**	−0.19**	−0.15*	−0.21**	Various	−0.22**
Nizhny Novgorod	−0.15*	−0.13*	−0.10	−0.13**	−0.13**	−0.10**	−0.06	Various	−0.08*
Ufa	−0.19**	−0.19**	−0.11	−0.09	−0.14*	−0.19**	−0.19**	Various	−0.14**

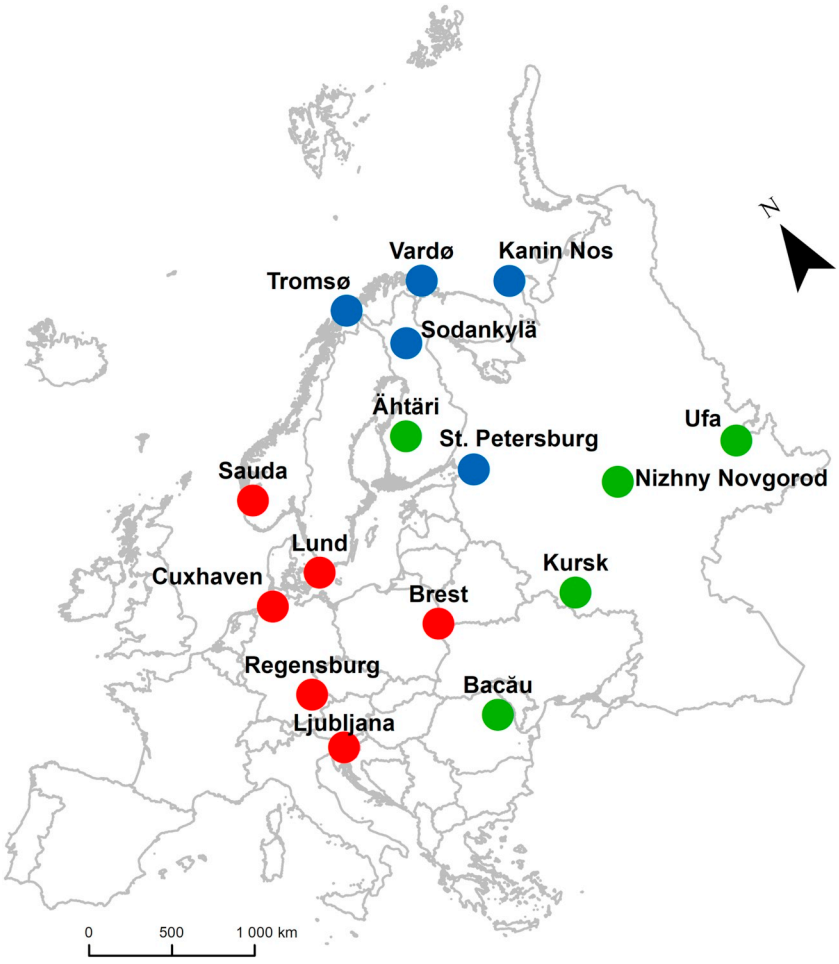

Fig. 7. Stations selected for the sensitivity study. Colour describes the tendency of trends of S/P (1961–2010, November–April) to grow (blue; 'Positive' in Table 3) or decline (red; 'Negative' in Table 3) with growing threshold temperature, T_t. The green colour indicates a negligible or unclear tendency ('Various' in Table 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

station, we also calculated the trend of S/P for all European stations aggregated together: it amounts to −0.12%·year^{-1} (significant at the 5% level). The negative trend of S/P is accompanied by an increase in liquid precipitation (0.55 mm·year^{-1}) and a decrease in solid precipitation (−0.26 mm·year^{-1}). A notable shift occurred in 1986 when S/P dropped rapidly, while the liquid precipitation increased and solid precipitation decreased considerably (Fig. 6). Low S/P prevails since 1986 and only two years with higher proportion of solid than liquid precipitation occurred after 1986 (1995 and 2010), although an increase in S/P is clearly visible since then, particularly in latter years

(2008–2010).

The main reason for the decrease of S/P in Europe is probably the increase in winter temperature (Klein Tank et al., 2002). Pearson correlation coefficient between daily S/P and daily mean temperature between November and April is significantly negative in western and central Europe (around −0.7), while in eastern Europe, it remains negative but lacks significance. Rising temperature is a crucial factor in the precipitation phase change over large parts of Europe, but its influence declines towards eastern Europe where winter temperature usually remains below 0 °C. In these regions, S/P is not influenced by rising temperature because average daily temperature during winter months does not exceed 0 °C, despite its increase. S/P may also be affected by long-term changes of circulation (and, consequently, temperature). Lower values of S/P due to a higher frequency of penetration of warm air masses may change the near-zero trend to negative, especially if this occurs near the end of the studied period.

We show in the previous section that temperature-based trends tend to be overestimated (i.e., are less negative than the real trends), the average overestimation over all Czech stations being $-0.2\%\cdot year^{-1}$. This suggests that also the S/P trends in Europe are probably overestimated; that is, S/P declines even faster or grows more slowly in reality than what we show in Fig. 5a.

The comparison of our study with others is complicated due to the lack of relevant studies of changes in precipitation phase in Europe. In Finland, Irannezhad et al. (2017) detected negative trends in S/P at one out of three analyzed stations between 1959 and 2008, magnitudes of all trends being close to zero. Nevertheless, this study is incomparable with our results because it analyses S/P trend for whole year, whereas we consider only cold half year. The other studies that exist for Europe are hardly possible to compare with our study – Marty and Meister (2012) and Schöner et al. (2009) analyse high mountain stations in the Alps and Twardosz et al. (2012) analyse one long time series starting in the second half of the 19th century.

2.3. Sensitivity to threshold temperature

Finally, we examine whether, and how much, the trends in S/P are sensitive to the threshold temperature. Different single threshold temperatures (−1.0, −0.5, 0.1, 0.6, 1.1, 1.6, and 2.1 °C) separating solid and liquid precipitation, as well as one pair of two threshold temperatures separating solid from mixed and mixed from liquid precipitation (0 °C and 2 °C, respectively) are applied at selected European stations to find out how this selection affects trends. For this purpose, we randomly select 16 stations that cover the whole analyzed area (see Table 3 and Fig. 7 for their names and locations). Mixed precipitation in the variant with two threshold temperatures is equally divided into rain and snow.

Table 3 indicates that the sensitivity of trends in S/P to the choice of threshold temperature is usually small; the differences between the lowest and highest trend fall between 0.08 and $0.20\%\cdot year^{-1}$ at most stations. The trend values corresponding to two threshold temperatures (rightmost column in Table 3) always fall within the range of trends for single threshold temperatures.

Table 3 together with Fig. 7 suggest that the change in S/P trends with changing T_t is not uniform: there are stations where trends increase (i.e., become less negative or more positive) with growing T_t (blue in Fig. 7) as well as those where trends decrease with growing T_t (red in Fig. 7); at some stations, the tendency is unclear (green in Fig. 7). There is no clear geographical dependence of the sensitivity of trends to threshold temperature in Fig. 7. It may, nevertheless, be tempting to say that the stations with negative sensitivity (red) tend to be located in the belt of high negative S/P trends and share a low occurrence of solid precipitation.

Trends corresponding to the threshold temperature determined from the separation between solid and liquid precipitation at Czech stations, 1.1 °C, exhibit smallest differences from the trends for other threshold temperatures. Furthermore, differences between trends for single threshold temperatures and for two threshold temperatures are smallest for the regional threshold temperature that we use (1.1 °C). Since the method of two threshold temperatures can be expected to be more accurate and T_t of 1.1 °C yields trends closest to it, we are convinced that our choice of the threshold temperature is near its optimum value, that is, that we can consider the regional threshold temperature of 1.1 °C to be a reliable value for the determination of precipitation phase in Europe.

3. Conclusions

In this study, we estimate changes in precipitation phase in cold months (November–April) at European stations. Because information about precipitation phase is usually not available to us there, the threshold temperature, which discriminates solid and liquid precipitation phase, is first determined at stations in Czechia where all necessary information is available in sufficient quality. We opt for daily mean temperature as threshold temperature because the dependence of probability of precipitation phases on temperature is much smoother for mean than for both maximum and minimum temperatures. The value of the threshold daily mean temperature is determined as 1.1 °C, which is in agreement with previous studies.

The trend of S/P between 1961 and 2010 is $-0.12\%\cdot year^{-1}$ for all European stations together. The belt of rapidly decreasing S/P (between −0.2 and $-0.9\%\cdot year^{-1}$) extends from the Scandinavian coast towards central Europe and ends in southeastern Europe. The negative trend of S/P in this belt is in general a result of increasing liquid precipitation and declining solid precipitation, probably due to rising winter temperatures at most stations and a modification of atmospheric circulation. The S/P trends are less negative towards northeastern Europe, and four stations in Russia even exhibit a slightly increasing trend of S/P. A comparison of trends based on threshold temperature with the exact trends in S/P at the Czech stations suggests that the method employing threshold temperature tends to overestimate trends, that is, tends to make them more positive or less negative. In result, real trends in the ratio of solid precipitation are smaller, that is less positive or more negative, and the decline of snow precipitation is likely somewhat faster than what results of this study display.

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